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AH-1Z INITIAL FLYING QUALITIES DEVELOPMENT

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ABSTRACT

The United States Marine Corps' H-1 Upgrades program has been developed to produce advanced aircraft to replace the aging fleet of AH-1W and UH-1N helicopters. The new AH-1Z and UH-1Y are near total redesigns of the baseline aircraft to provide the Marine Corps with flexible and powerful attack and utility helicopters for the 21st century. The first AH-1Z is a structural and aerodynamic demonstrator, and it is currently in the initial stages of Development and Envelope Expansion flight testing as a part of Engineering and Manufacturing Development. Some of the upgrades that are being evaluated on the first AH-1Z are the new four bladed composite main and tail rotor systems, new drive systems, new wet wings, new landing gear, new hydraulics and flight controls, and strengthened structure. New advanced Integrated Avionics and Weapons Systems are included in the H-1 Upgrades program but are not installed on AH-1Z #1. This paper will briefly outline the course of development and envelope expansion to date and then highlight several lessons learned during this initial testing.

INTRODUCTION

The United States Marine Corps' H-1 Upgrades program has been developed to produce advanced aircraft to replace its aging fleet of AH-1W and UH-1N helicopters. The primary objective of the program is to provide cost effective weapon systems that meet all mission requirements, are highly affordable, economically maintained, and achieve a high readiness rate in a wide variety of conditions. To achieve these goals the program includes the development of a new composite four bladed rotor system that is designed to provide higher aerodynamic performance, increased damage tolerance, lower maintenance, light weight, and a 10,000 hour life expectancy. To further enhance maintainability, the UH-1Y and AH-1Z are

designed with over 85% common parts and systems. Range on both aircraft should be significantly increased through the use of wet wings on the Zulu and through structural redesign and increased length to accommodate internal fuel cells on the Yankee. Maximum gross weight on both aircraft has been increased to 18,500 pounds to accommodate increased fuel, payload, and modernized systems. A new drive system in both aircraft is designed to transfer more of the power produced by twin GE T-700 engines to the rotors. Flight controls and hydraulics systems are also redesigned, though the aircraft maintain the mechanical tube and bellcrank technology of their predecessors. The Stability and Control Augmentation System is also similar to the previous H-1 design, but a new 4-axis Automatic Flight Control System is added to reduce pilot work load and increase safety in night, low-altitude, and adverse weather flight regimes. Finally, an Integrated Avionics and Weapons System is designed to give the aircraft the technological advantages needed on the most modern battlefield to survive and win.

The AH-1Z design specification has established goals for the initial developmental testing of the aircraft performance parameters (table 1). In addition to the numbers presented in the table below, the AH-1Z specification requires that the handling qualities be at least as good as its predecessor, the AH-1W.

Performance Parameter	AH-1Z Specification	AH-1Z Tested-to-Date
V_H (Max level flight speed in Spec Configuration at Design Gross Weight)	140	140
V_{NE} (Velocity Not to Exceed)	222	222
V max side	35	45
V max rear	30	35

Table 1

The first AH-1Z is a structural and aerodynamic demonstrator, and it is currently in the initial stages of Development and Envelope Expansion testing as a part of the Engineering and Manufacturing Development program. Some of the upgrades that are being evaluated on AH-1Z #1 are the new four-bladed composite main and tail rotor systems, new drive systems, new wet wings, new landing gear, new hydraulics and flight controls, and strengthened structure. The advanced Integrated Avionics and Weapons System is not installed on AH-1Z #1.

Though there have been many lessons learned during development and test, particular emphasis will be placed on three areas of initial development and optimization of the aircraft flying qualities.

1. Development of the mechanical flight control system with a side-hand cyclic control to produce a blend of satisfactory control response and control harmony while avoiding potential pilot induced oscillations.

2. Achieving satisfactory longitudinal flying qualities through tail configuration, flight control mechanical characteristics, and SCAS development.

3. Achieving satisfactory lateral and directional flying qualities through tail configuration, flight control mechanical characteristics, and SCAS development.

In each of these three areas there were concerns during the design phase that the desired flying qualities may not be initially achieved. Also, in each area a risk reduction plan was formulated during early test planning. In all three cases, the results of early EMD testing turned out to be a careful balance between aircraft response, aircraft stability, aircraft performance, base-line design, cost, and schedule.

THE AIRCRAFT

AH-Z1 #1 is a highly modified AH-1W designed and built by Bell Helicopter, Textron Inc. (BHTI). The main and tail sections of the fuselage are similar in dimension to the AH-1W, but they are structurally modified to carry different and higher loads.



Figure 1 - AH-1Z #1 in Flight

The main rotor system is a composite four-bladed, semi-rigid, soft in plane, hingeless, and bearingless design. The system stacks two composite main rotor yokes at 90 degrees. This "stacked" design reduces complexity of the rotor hub and is designed to reduce manufacturing and maintenance efforts. The yokes carry centrifugal forces and provide structural flexure for rotor flapping, feathering, and lead-lag. The rotor blades are attached to the yokes via the torsionally stiff main rotor cuffs, which also transfer rotor pitch forces from the control system to the main rotor yoke. The inboard end of the main rotor cuffs contain fluid-elastic lead-lag dampers to allow in-plane motion of the rotor. The main rotor system has a diameter of 48 feet and blade chord is 25 inches with a hyperbolic shaped tip.

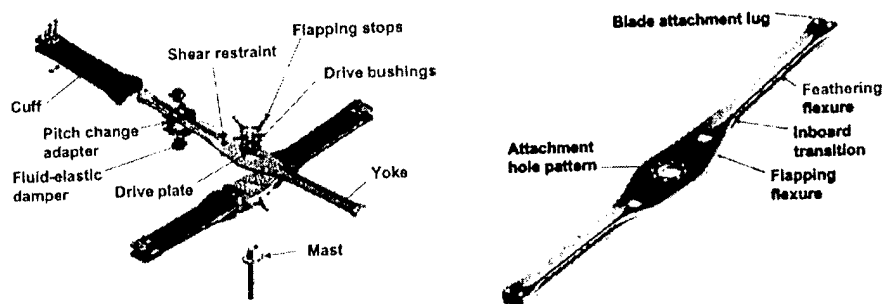


Figure 2 – AH-1Z Main Rotor and Yoke Diagram

The tail rotor is a pusher type vice the tractor tail rotor of the UH-1N and AH-1W. This location is designed to reduce in-flow interference from the vertical fin. The tail rotor also makes use of composites and elastomerics to achieve simplicity of design, low maintenance, reduced weight, 10,000 hour life, and ballistic tolerance. The four-bladed tail rotor system consists of two stacked teetering heads. The blade pairs are separated axially to provide for hub attachment hardware and operational clearance. This design provides four bladed performance with the structural and mechanical simplicity of a two-bladed teetering rotor. Like some conventional teetering rotors, this system uses an elastomeric bearing to provide the flapping degree of freedom. However, in this design, the torsional stiffness of that same bearing has been designed to transmit rotor torque and provide adequate softness in the rotor plane to relieve loads from two per rev coriolis effects associated with four bladed systems. The tail rotor blades have a diameter of 9.75 feet and a chord of 8 inches.

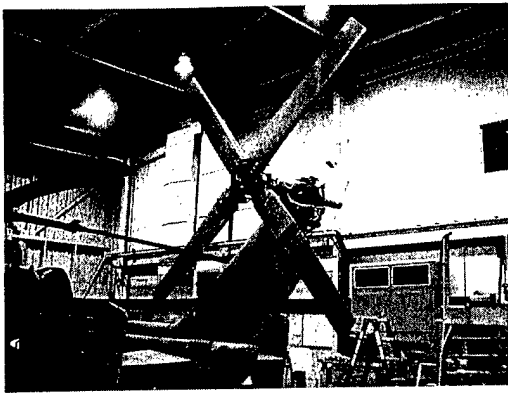


Figure 3 - AH-1Z #1 Tail Rotor

The flight control system is mechanical, augmented by two redundant hydraulic systems. All cockpit flight controls have direct mechanical linkages to the control surfaces. While it is a mechanical flight control system, hydraulic boost is required for controlled flight due to the forces required to affect pitch on the main rotor system. Both the front and rear cockpits have identical flight controls, including a side-hand control cyclic. The side-hand control cyclic was selected in an attempt to make both cockpits identical and to maximize the use of the minimal space available in an attack helicopter cockpit.

The horizontal stabilizer is a fixed angle of incidence airfoil, although it is adjustable between flights on the test aircraft only. The horizontal stabilizer has fixed vertical end plates attached to each side. The angle of incidence on the left and right endplates can also be varied between flights. This has the advantage of allowing the test team to rapidly evaluate flying qualities and loads with various configurations of horizontal stabilizer and end plates. The vertical fin is also an airfoil designed to increase directional stability and reduce power requirements on the tail rotor in forward flight.

The stability and control augmentation system (SCAS) on the AH-1Z #1 is designed to both feed forward control inputs and provide aircraft rate damping. It is capable of using rate, acceleration, and N_z feedback to shape aircraft responses. The SCAS actuators are reduced authority, in the realm of 30% of total control authority at this time. Development of the SCAS on AH-1Z#1 is planned to feed forward into development of the full 4-axis AFCS on the production aircraft.

FLIGHT TEST APPROACH

The development and envelope expansion phase of flight testing was designed to finalize the physical configuration of the aircraft and provide an envelope to allow the completion of the rest of the EMD flight test schedule, including systems and weapons testing. This testing has been planned and conducted by an Integrated Flight Test Team consisting of BHTI and USMC/NAVAIR pilots and engineers. Initial testing was conducted at the BHTI Flight Research Center in Arlington, Texas. Following four months of flight tests the test program has moved to its present location at NAS Patuxent River, Maryland. Testing during this phase includes integration of basic systems, restrained ground drive system endurance, ground and flight torsional stability, ground and flight aeroelastic stability, basic aircraft configuration development, initial handling qualities evaluation, stability and control augmentation system (SCAS) development, initial performance evaluation, interim loads and vibrations definition, and weapons stores carriage evaluation.

To incrementally evaluate all of the critical test areas during initial aircraft development, a standardized series of envelope expansion tests has been used to open a safe test envelope. This series of tests was used in initial testing, after CG/weight changes, and after significant modifications to airframe or SCAS. Altitudes, airspeeds, angle of bank, and other flight test parameter were standardized early in the test planning to the maximum extent possible so that each engineering discipline on the test team could use the same data base and minimizing the number of data points required.

From an initial vertical takeoff, both qualitative and quantitative evaluations were conducted. Quantitative engineering tests included rotor excitations for aeroelastic stability, control response in all axes, and torsional excitations. From a hover, the envelope was expanded through longitudinal accelerations and decelerations and then low airspeed paced level flight to 60 knots forward, 45 knots left and right, and 35 knots rearward. Following the low altitude evaluation, low airspeed flight was evaluated up to 80 knots and in normal approaches and pattern maneuvers. Upon satisfactory completion of tests in the airfield area, the test sequence proceeded up to forward flight testing. These tests expanded airspeed in 10 knots increments, pausing every 20 knots for aeroelastic excitations and normal turns. Smaller incremental steps in airspeed were not needed, but they had been planned for if adverse trends such as poor rotor system stability, low torsional damping, or poor handling qualities had occurred. Following expansion to maximum level flight airspeed, V_H , dives were conducted to the limit speed, V_{NE} . Additional tests

were then conducted to include loads expansion with level turns and rolling pullouts, autorotational entry and descent, and a full series of longitudinal and lateral-directional handling qualities evaluations.

The goals for the initial handling qualities development were fairly clear- to develop Level 2 handling qualities (HQR 4, 5, or 6) with SCAS off and Level 1 handling qualities (HQR 1, 2, or 3) in the primary flight mode, SCAS on. The pilots use the Cooper-Harper pilot rating scale for assigning HQRs to mission related flight tasks. A full set of traditional engineering flying qualities data was also collected for each configuration. The handling qualities goals were then balanced against structural loads, vibrations, aircraft performance and other factors in deciding what approach to take and what level to achieve in correcting deficiencies.

Several concepts were used to ensure safety during the initial envelope expansion. All testing was conducted with SCAS off prior to SCAS on to ensure that the basic aircraft handling was safe prior to engagement of the stability system. Telemetry was used for all initial flights, with limit and trend monitoring by both engineers in the TM room and a BHTI developed computer parameter monitoring system, CAFTA. Additionally, a remote "virtual" TM room was created at BHTI, which allowed design and technology engineers from BHTI to monitor flight tests real-time and communicate to the on-site test director. This remote TM room increased the number of engineers available to support test flights while minimizing costs associated with on-site operations. Pilot inputs were used for rotor system and torsional excitations prior to use of a SCAS exciter box to provide build-up to more strenuous excitations. During all exciter box induced excitations, the pilots were able to disconnect the excitations immediately through the normal cyclic mounted SCAS disengage button.

TEST ISSUES

Lateral Control Response

There were several concerns that drove the plan for initial flight testing. Perhaps the most prevalent concern prior to initial flights was based on the use of mechanical side-hand controllers in both cockpits. While the use of mechanical linkages instead of a digital flight control system eliminated the potential for software induced control issues, the mechanical system posed unique issues when coupled with the highly responsive rotor system. Flight testing conducted by BHTI in 1989 on the AH-1 4BW Demonstrator had indicated that the rotor system design had

the potential for inducing lateral pilot induced oscillations (PIO), even when coupled with a full-size center cyclic. Simulator evaluations provided further indications of potential PIO issues with the increased sensitivity of a side-hand controller. The test team was faced with planning for the risk of the side-hand control cyclic combined with the roll sensitivity of the rotor system to create potentially dangerous handling qualities in the low altitude environment.

The test team mitigated the risk of lateral PIO through two methods during initial flight testing. First, the aircraft was configured for maximum roll inertia with full wing stores loading. Flights were flown in configurations that incrementally provided decreased roll inertia, down to a final clean wing configuration. Secondly, a series of lateral bellcranks was evaluated in increasing increments of sensitivity. Beginning with 60% of the design control sensitivity, these bellcranks were evaluated for safety of flight and desired lateral handling qualities. The 60% bellcrank provided less input to the rotor system for a similar cyclic input than the design 100% bellcrank, while the 120% provided an increased input to the rotor for the same cyclic input. The potential lateral PIO has not materialized as an issue during initial developmental testing. The differing bellcrank configurations were evaluated throughout the current flight test envelope. Development of lateral control sensitivity has been temporarily halted at 120% of the design sensitivity, which has given the desired lateral control response while the four test team pilots have noted no tendency to PIO to date. Engineering data has indicated several instances on landing and takeoff from a hover that show potential PIO with lateral cyclic getting out of phase with aircraft response for a very short time (for approximately 2-3 cycles). However, the condition is so short lived that it is not recognized by the pilots and is rapidly damped out. It has also been shown to occur primarily only during a pilot's first flight with this control configuration. Besides giving the most desired control response, the 120% bellcrank also has also provided the best feel of control harmony with the longitudinal cyclic control. Evaluation of the lateral control sensitivity will continue during future handling qualities tests, particularly as the test envelope opens up to include more aggressive maneuvers. Through deliberate and incremental evaluations of varied roll inertia and lateral control sensitivity, the test team has developed a potential lateral control configuration that meets the test goals and successfully mitigated the risk of lateral PIO.

Longitudinal Flying Qualities

Initial concerns over longitudinal flying qualities came from several unknowns. The major design concerns effecting longitudinal stability came from increased size of the weapons pylons, increased fairing around the larger transmission and auxiliary power unit area, new 4-bladed rotor

system, and sizing of the horizontal stabilizer. The horizontal stabilizer was initially designed to the minimum size that would result in satisfactory handling qualities. The benefits of the smallest possible horizontal stabilizer were reduced drag for better performance, reduced weight in the CG-sensitive tail area, reduced loads on the tail boom and horizontal stabilizer, and carryover from the AH-1W. However, the larger weapons pylon and fairing area had potential to have interference effects on the horizontal stabilizer, and the weapon pylons' wing shape could have a destabilizing effect on the aircraft. It was also unclear if the horizontal stabilizer would offset the new rotor system for angle of attack stability up to a desired g load and with satisfactory longitudinal response for an attack aircraft. The AH-1Z developmental team recognized these risks and planned the time, budget, and assets for full evaluation of the longitudinal flying qualities, SCAS development, and if needed, a larger horizontal stabilizer.

Initial forward flight tests demonstrated that the aircraft had poor angle of attack stability and generally marginal longitudinal handling qualities. Static longitudinal stability was positive but weak. Figure 4 illustrates the essentially constant fore/aft cyclic position within ± 12 knots of trim. Maneuvering stability was also positive but very weak. Airspeed and altitude maintenance in level flight with SCAS off required constant small pilot corrections. The non-augmented aircraft was extremely responsive in pitch. Nz control was unpredictable and could respond in a g-load run-away during moderate longitudinal cyclic inputs. The longitudinal long term dynamic response (phugoid) was aperiodic and divergent. Figure 5 illustrates the divergent pitch rate and Nz responses during long-term testing. The combination of the divergent long-term and the unpredictable Nz-response forced the pilots to exercise significant caution during the initial open-loop testing. Furthermore, the aircraft's pitch responsiveness appeared to increase with speed such that pilot workload was extremely high in the longitudinal axis during high speed dives.

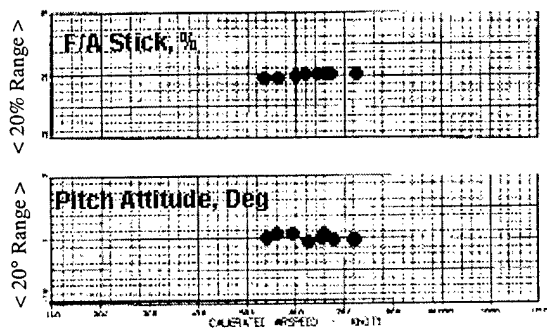


Figure 4 - Representative Static Longitudinal Stability

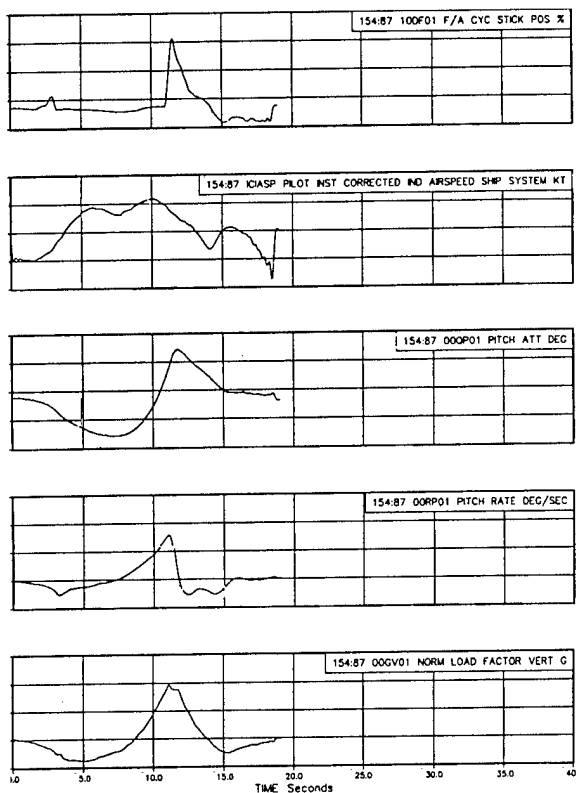


Figure 5 – Representative Longitudinal Long-Term, Artificial Excitation

Initial efforts to improve longitudinal handling qualities included changes in the angle of incidence of the horizontal stabilizer and development of the SCAS system in the pitch axis. Through SCAS development, long term dynamic stability was significantly improved. Furthermore, through the use of SCAS acceleration cues and Nz feedback loops in the pitch axis, the pitch response and Nz control was made more predictable up until the pitch SCAS servo saturated. After some trial and error, a balance was achieved between an improved pitch response and avoidance of SCAS saturation. The test team had less success with the angle-of-attack adjustments on the horizontal stabilizer. The effects of the fuselage, weapons pylons, and rotor downwash were disturbing the airflow over the horizontal stabilizer. Evaluations of structural loads on the horizontal stabilizer and longitudinal flying qualities showed no significant changes with variation of the stabilizer angle of incident. So while major improvements in longitudinal dynamic stability were achieved through the SCAS development, not much improvement was achieved in the static stability or maneuvering stability. Essentially, longitudinal handling qualities with SCAS off were in the Level 2 arena, but pilot workload was high enough to combine with specification issues to drive a modification to the aircraft design.

The first significant change in aircraft configuration will be the horizontal stabilizer. The size of the horizontal stabilizer will be significantly increased with the addition of 21 inch extensions on each side of the tailboom. This will increase the area of the stabilizer approximately 60% with a 35% increase in span. This new stabilizer should provide increased longitudinal static stability and maneuvering stability. It should also improve the angle-of-attack stability, long-term longitudinal response, and Nz control beyond what the SCAS has already achieved. All physical configuration changes to the aircraft raise potential for changes in other areas. The changes to the size of the horizontal stabilizer raise issue with lateral-directional flying qualities, tailboom loads, vibrations, and aircraft performance. Potentially, the effects on lateral-directional flying qualities and aircraft performance may be positive. Moving the vertical endplates further out into cleaner air may improve the effectiveness of the endplates and increase lateral-directional stability. Additionally, the improved airflow over the endplates may reduce drag, improving aircraft performance. Conversely, the increased size of the stabilizer will bear drag and loads penalties that must be evaluated to achieve the desired handling qualities, maintain acceptable loads on the tailboom, and meet critical aircraft performance parameters.

Further testing will be required to evaluate the effectiveness of the modified horizontal stabilizer configuration. The stabilizer will be varied in

angle of attack to attempt to identify the most efficient configuration. Additionally, the vertical endplates will be varied in angle of incidence to evaluate their effectiveness in the new airflow region.

Lateral Directional Flying Qualities

Another area of concern entering into initial flight testing was the potential for lateral-directional oscillations (LDO) or random yaw kicks (tail wag). Additionally, there was also concern for potential excitation of tail boom structural modes by either poor lateral-directional flying qualities or attempts to control such issue with SCAS. The concern for the lateral-directional stability stemmed from the unpredictability of airflow over the aft end of the aircraft, including the horizontal stabilizer, vertical endplates, tail rotor, and vertical stabilizer. Initial flight testing demonstrated an easily excited LDO that was small, well-damped, and easily suppressed with minimal pilot workload. This oscillation, in the realm of 1-2 degrees at $\frac{1}{2}$ Hz, was evident in all configurations of the vertical endplates and was eliminated with SCAS. Because it was so small and easily suppressed (resulting in Level 2 handling qualities SCAS off), the LDO was not significant enough to drive a change in aircraft configuration.

However, evaluations of the effectiveness of the vertical endplates and vertical stabilizer indicated that the endplates were not flying in smooth air and were essentially providing minimal effectiveness as airfoils. Flight tests have demonstrated the existence of a two to three degree "dead band" around trim in straight and level flight. Inside this dead band area, pedal input requirements for small directional changes were increased significantly. For instance, from an out of balance condition laterally (ie; ball out of center) a small pedal input moved the ball rapidly toward center. As the ball neared center, however, pedal input requirement increased significantly to bring the aircraft into balanced flight. Another symptom of the dead band was that in-between test points, pilots often flew in a slightly out of balance condition such that the tailboom was on one side of the dead band or the other. This had the effect of reducing workload in the directional axis.

The current approach to eliminating these nuisance modes in the lateral and directional axis works hand in hand with the current configuration change to improve longitudinal flying qualities. By increasing the size of the horizontal stabilizer, the vertical endplates have moved 21 inches out on both sides. It is believed that this will put the endplates in clean airflow and significantly increase their effect on lateral and directional stability. The test team hopes to see increased damping of the LDO and elimination of the dead band. Further testing will be conducted to evaluate the new configuration.

CONCLUSION

The Marine H-1 Upgrades program leverages new technology, combined with some existing aircraft structure and systems, to achieve highly affordable weapon systems that can carry out future attack and utility helicopter missions. Under these circumstances, development must be a very careful balance of all factors to include flying qualities, performance, cost, schedule, safety, reliability, and maintainability. To efficiently achieve this balance, planning must begin early, risks must be recognized, and risk reduction planned for. After aircraft testing begins, there is a continuous chain of decision points, and there must be an on going balance as those decisions are made.

During initial flying qualities development on the AH-1Z, some early risk analysis turned out to be less significant than anticipated, while other risk areas had significant impact and required a configuration change. No configuration change has been taken lightly. The decisions were based on full sets of qualitative and quantitative data, and were made to minimize negative impacts in areas such as cost and performance, while maximizing positive impacts on areas such as handling qualities and safety.

Thus far, the AH-1Z is on track and leading the way to providing the USMC with attack and utility helicopters that can dominate the battlefield of the future.

LESSONS LEARNED

-Planning: Things don't go as planned. Early planning, identification of potential risk items, and a good risk mitigation plan can greatly reduce the negative impact of unexpected test results. While it is impossible to predict all risk areas, on the H-1 Upgrades program an integrated and thorough process of identifying risks has allowed safe build-up in flight test. For example, during early planning the test team developed risk mitigation plans in the form of three varied lateral control bellcranks for incremental control sensitivity changes, schedule and budget for a larger horizontal stabilizer, and detailed build-up plans for flight safety concerns. In each case the planning paid off in safety, schedule, budget, and/or optimization of the aircraft flying qualities.

-Planning: Good planning can save time and money. In an effort to reduce overall development costs of the AH-1Z, testing was planned to maximize concurrency of data points. From the initial test planning stages, a concerted effort was made to standardize configurations and data point

parameters throughout the varied test plans. This required some compromise by the various engineering disciplines. In the vast majority of cases however, the test team was able to agree on test points that would produce satisfactory data for analysis by all disciplines. This allowed for more cost and schedule efficient flight testing.

-Flight Test Methodology: A standardized flight test approach can increase safety, save money, and expedite schedule. The AH-1Z test team has developed a fairly standardized procedure for development of an initial envelope and evaluation of aircraft physical configuration changes. The procedure was designed to maximize the number of test points taken per flight for data across the spectrum of engineering disciplines. Automated limit monitoring and trend analysis, and the combination of on-site and remote telemetry rooms have provided excellent test engineer support to the cockpit aircrew. Familiarity with the procedures has reduced time for test card preparation and flight briefing, time for in-flight transitions between data points, and time for data analysis. Furthermore, standardization has increased safety through standardization of pilot and engineer procedures and responsibilities during test flights. Using standardized test sequences has not only increased safety for the AH-1Z test team, but it has also significantly reduced the number of test points and flight hours required to develop and qualify the aircraft.

-Aerodynamics: Airflow is hard to predict. Like many other developmental programs, the AH-1Z program has been challenged during flying qualities development by the difficulty of predicting complex airflow across the tail section of the aircraft. Flight test may be the only way to fully develop an understanding of the complexities of airflow on a rotary wing aircraft. The program has not experienced most of the worst case possible problems such as resonance, tail wag, or severe LDO. However, the original design did not produce the desired aerodynamic forces for satisfactory flying qualities in the longitudinal, lateral, or directional axis. By recognizing some risk with aerodynamic predictions and planning for early flight test evaluations of identified question areas, the test team was able to mitigate some of these costs and trade offs early on in the test planning process.

-Balance: Most modern day flight test programs must achieve a balance between flying qualities, performance, maintainability, reliability, schedule, and budget. As testers we naturally want to develop the absolute best aircraft that we can in terms of flying qualities and performance. The reality of cost as an independent variable forces well thought-out decisions on the prospective trade-offs between cost and performance. During initial development of the AH-1Z, the optimization of flying qualities has been carefully balanced against the cost of aircraft

physical configuration changes. The test team has recommended changes to the aircraft configuration, such as a larger horizontal stabilizer, that have carefully balanced aircraft performance concerns with associated costs.

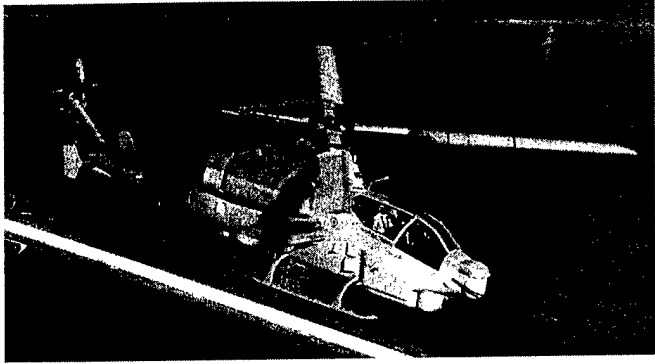


Figure 6 – AH-1Z #1